

DESIGN AND SIMULATION OF A SINGLE CYLINDER HIGH SPEED SPARK
IGNITION LINEAR ENGINE WITH SPRING SYSTEM

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SUPERVISOR'S DECLARATION

I hereby declare that I have checked this thesis and in my opinion, this thesis is adequate in terms of scope and quality for the award of the degree of Doctor of Philosophy in Automotive Engineering.

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I hereby declare that the work in this thesis is my own except for quotations and summaries which have been duly acknowledged. The thesis has not been accepted for any degree and is not concurrently submitted for award of other degree.

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LIST OF SYMBOLS

α	Coefficient of thermal expansion
β	Coefficient of convection
δ	Displacement, deflection of the spring
γ	Gas specific heat ratio (C_p / C_v)
ρ	Density of material
ε	Strain
σ	Stress
τ	Shear Stress
τ_{\max}	The maximum of shear stress
Δ	different
ΔT	Temperature different
Ω	Domain
Ω_e	The element of domain
Γ	The boundary of surface
Γ_1, Γ_2	The boundary of surface on the portions 1 and 2 respectively
a	The parameter of Wiebie
A	Area
b	Cylinder bore,
$Bmep$	Break mean effective pressure
C	Constant
C_b	Patton proportional constant of bearing (3.03 X10 ⁻⁴ kPa-min/rev-mm)

List of Symbols: Continued

C_g	Bishop gas load constant ($C_g=6.89$)
C_{ps}	Patton proportional constant of skirt (294kpa-mm-s/m)
C_{pr}	Patton proportional constant of rings (4.06×10^4 kPa-mm ²)
C_s	Patton proportional constant of seals (1.22×10^5 kPa-mm ²)
d	Wire diameter
D	The mean of diameter of coil
D_{as}	The accessory or balancing shaft bearing diameter
D_{cb}	The connecting rod bearing diameter
D_{mb}	The main bearing diameter
f	Frequency
f_n	The natural frequency
f_{mep}	The friction of mean effective pressure
F	Force, Loading of spring
F_c	The force of combustion
F^e	The element load vector
F_f	The force of the friction
F_l	The force of the loads
F_s	The force of the spring
g	Acceleration gravity, The internal heat generation per unit volume in a three-dimensional domain
G	The shear modulus
$k_x k_y k_z$	The conductivities of an orthotropic solid
K	The stress constrain factor

List of Symbols: Continued

K	Bishop friction K constant (0.14 for spark ignition engines and 0.29 for diesel engines)
K^e	The stiffness matrix
L	The free length of spring
L_b	The length of bearing
L_{mb}	The total main bearing length per number f cylinders
L_{cb}	The rod bearing length
L_{as}	The total length of all accessory shaft bearing per number of cylinders
m	The parameter of Wiebe
m	The number of pistons per rod bearing
m	mass
M^e	The element mass matrix
mps_f	The mean piston speed factor
$mpss_f$	The mean piston speed square factor
n	The number of active coil
n_b	The number of bearing
n_c	The number of cylinders
n_r	The number of cylinder
N	The engine speeds
P	Pressure
P_a	The atmospheric pressure
P_f	The peak cylinder pressure factor
P_f	The fiction power
P_i	The intake manifold pressure

List of Symbols: Continued

Q	Heat release
Q	The number of inactive coil
Qe	The vector of internal force
r	Compression ratio
s	The piston stroke
S	Spring deflection
S_f	Safety level
t	The time variable of combustion
t_{comb}	The period of combustion
T	Temperature
T_{∞}	The ambient temperature ambient
U	A characteristic velocity
\bar{U}_p	The average of instantaneous piston speed
V	Volume
V_d	The displacement volume
w	The weight function
W	The rate of heat release
x	The displacement of the piston assembly
X	The mass fraction burnt
X	The design vector
X_{max}	The maximum of mass fraction burnt

LIST OF ABBREVIATIONS

BDC	Bottom Dead Centre
BG	Brush Cutter
CAD	Computer-Aided Design
DOF	Degree-of-freedom
FEM	Finite-Element Method
FEA	Finite-Element Analysis
MOA	Multilevel Optimization Approach
ODRO	Operation Design Requirement Optimization
TDC	Top Dead Centre
SAE	Society of Automotive Engineers
SAE6150	SAE standard of chrome-vanadium alloy steel wire

ABSTRACT

This thesis deals with the design of a single cylinder high-speed spark ignition linear engine with a spring system return cycle. The main objective of the research is to design and analyse a free piston linear engine that is easy to start, easy to maintain and easy to control. The unique design of the spring as a return cycle in a free piston linear engine is presented and its effects on engine performance and motion are discussed. The engine performance has been predicted the aim is to design a linear engine particularly for the spring system. The spring design has been optimised by using a multilevel optimization approach. Based on the optimisation of the spring design, the linear engine geometry design has been conducted. The performance of the linear engine design has been measured and the results compared with the predicted performance. Besides which the motion of the linear engine has been studied; however, friction affect show the rotated of the piston. It is necessary to modify the spring mechanism to ensure that the scavenging process works properly. Two scenarios such as the removal of the bottom part of the piston skirt and adding a lock to the connecting rod are recommended, based of structural stress and thermal-structural stress analysis. Software has been used in the research to analyse the design of the free piston linear engine with a spring system, including GT-Power, SolidWorks, Matlab, Algor, and Spread-Sheet. The model has been built using GT-Power to predict the engine performance. To validate the model, it has been assessed with the original engine manual and experimentally. Three step multilevel optimisation of the spring geometry has been carried out by using Matlab and Spread-Sheet. SolidWorks has been used to design all of the components and for the assembly of the linear engine. Cosmos motion, which is a part of the SolidWorks facility, has been used to analyse the piston dynamics of the linear engine. Once again, GT-Power has been used to analyse the effect of the spring design on the linear engine performance. For the modification of the design of the spring system, Algor has been used to analyse the thermal-structural stress of the piston and the connecting rod. Through step by step considerations started from building model to predict the performance of linear engine, to optimize the spring geometry design then continued build the free piston linear engine with spring system including design, analyses and modified. The result is a design which predicts the performance and the dynamics of piston motion. Only 50% of the 12 speeds sampled worked correctly. The rotation of the piston on the Z-ordinate can be fixed through modification of the piston or connecting rod. A design of a single cylinder high-speed spark ignition linear engine with spring system as return cycle has been carried out. Although the range of speeds was narrow compared to a conventional engine, the maximum power output is still higher. The final design result was 1.03 kW at 3.6 m/sec.

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ABSTRAK

Tesis ini berkaitan dengan merembentuk sebuah mesin pencucian bunga api berkelajuan tinggi yang berbentuk mesin linier dengan menggunakan sistem pegas sebagai kitar kembali. Tujuan utama kajian ini adalah untuk merembentuk dan mengkaji mesin linier putaran bebas yang mudah dimulakan, mudah dibuat penyenggaraan dan senang dikawal. Keistimewaan pegas sebagai kitaran kembali didalam mesin linier piston bebas telah ditunjukkan dan pengaruhnya keatas prestasi mesin dan pergerakannya dibincangkan. Prestasi mesin telah diramalkan mengikut rementuk mesin linier terutama menggunakan mekanisme pegas. Reamentuk pegas telah dioptimumkan dengan pendekatan pengoptimum secara berperingkat. Berdasarkan keputusan optimasi rementuk pegas, geometri daripada rementuk mesin linier telah dapat dilakukan. Prestasi rementuk mesin linier telah dikaji dan hasilnya dibandingkan dengan prestasi ramalan. Selain itu, daripada pergerakan mesin linier yang telah dipelajari geseran dapat ditunjukkan dengan pengaruh pusingan piston. Dengan itu pergerakan mekanisme pegas perlu ditukar untuk dapat memastikan proses menghapus sisa boleh bekerja dengan baik. Dua keadaan yang mana pemotongan bahagian bawah dinding piston dan penambahan kekunci pada rod penyambung dicadangkan mengikut kajian ketegangan struktur dan ketegangan terma-struktural. Beberapa perisian telah digunakan kerana untuk mengkaji rementuk mesin linear piston bebas dengan sistem pegas, iaitu GT-Power, SolidWorks, Matlab, Algor, dan Spread-Sheet. Sebuah model telah dibina dengan menggunakan GT-Power untuk meramal prestasi mesin. Untuk pengesahan model ini telah dibuat pemeriksaan dengan menggunakan buku panduan asli dan eksperimen. Dengan menggunakan Matlab dan Spread-Sheet untuk mendapat optimum peringkat ketiga bagi merembentuk geometri pegas. SolidWorks telah digunakan untuk merembentuk semua bahagian dan pemasangan mesin linier. Cosmos Motion yang merupakan sebahagian daripada kemudahan SolidWorks telah digunakan untuk mengkaji dinamik piston daripada mesin linier. GT-Power telah digunakan sekali lagi untuk mengkaji kesan daripada rementuk pegas pada prestasi mesin linier. Untuk mengubahsuai rementuk sistem pegas, Algor telah digunakan untuk mengkaji tegangan terma-struktur daripada piston dan rod penyambung. Melalui langkah demi langkah bermula daripada pertimbangan pembentukan model untuk meramal prestasi mesin linier, untuk optimasi perancangan geometri pegas seterusnya membina mesin linier piston bebas dengan sistem pegas, iaitu merembentuk, mengkaji dan mengubahsuai. Hasilnya adalah sebuah rementuk yang telah diramal prestasi dan gerak dinamik daripada piston nya. Dari 12 kelajuan sebagai pembolehubahnya hanya 50% kelajuan boleh bekerja dengan baik. Putaran piston pada paksi Z boleh diperbaiki dengan pengubahsuaian dari piston atau rod penyambung. Reamentuk mesin pencucian bunga api berkelajuan tinggi mesin linier dengan menggunakan sistem pegas sebagai kitar kembali telah dilakukan. Walaupun kelajuan mesin menurun berbanding dengan mesin konvensional, tetapi output kuasa maksimum masih lagi tinggi. Keputusan rementuk akhir adalah sebanyak 1.03 kW pada 3.6 m/saat.

REFERENCE

- Achten, P.A.J., van den Oever, J.P.J., Potma, J., and Vael, G.E.M., 2000, Horsepower with Brains: The Design of the Chiron Free Piston Engine, *SAE Technical paper* 2000-01-2545
- Achten, P.A.J., 2009, A Series Hydraulic Hybrid Drive Train, Off-Highway Directory, www.ifps.org | www.fluidpowerjournal.com (16 December 2009)
- Agrwal, G.K. 1978. Helical torsion springs for minimum weight by geometric programming, *Journal of Optimization and Applications*: Vol. 25, No. 2, pp:307-310
- Ahn, G.Y., Jeong, K.Y., 2004, Optimization of the spring design parameters of a circuit breaker to safety the specified dynamic characteristics, *International Journal of Precision Engineering and Manufacturing* Vol.5, No. 4, pp: 43-49
- Aichlmayr, H.T., 2002. *Design Considerations, Modeling, and Analysis of Micro-Homogeneous Charge Compression Ignition Combustion Free-Piston Engines*, PhD Thesis, The University of Minnesota.
- Aichlmayr, H.T., Kittelson, D.B. and Zachariah, M.R. 2002 A. Miniature free-piston homogeneous charge compression ignition engine-compressor concept—Part I: performance estimation and design considerations unique to small dimensions, *Elsevier Science, Chemical Engineering Science* 57, pp: 4161 – 4171
- Aichlmayr, H.T., Kittelson, D.B. and Zachariah, M.R. 2002 B. Miniature free-piston homogeneous charge compression ignition engine-compressor concept—Part II: modeling HCCI combustion in small scales with detailed homogeneous gas phase chemical kinetics, *Elsevier Science, Chemical Engineering Science* 57, pp: 4173 – 4186
- Algor. 2005. Finite Element Analysis in Practice. Algor. Pittsburgh. USA
- Allais, E., “Free-Piston Engine with Operatively Independent Cam”, U.S. Patent Application No. 416,959, Application filed September 9, 1982; U.S. Patent No. 4,480,599, Patent issued November 6, 1984.

- Annen, K.D., Stickler, D.B., and Woodroffe, J., 2003. Linearly-oscillating miniature internal combustion engine (MICE) for portable electric power, AIAA 2003-1113, 41st *Aerospace Sciences Meeting and Exhibit* 6-9 January, Reno, Nevada
- Annen, K.D., David B. Stickler, D.B., Woodroffe, J., 2008. Miniature Internal combustion Engine-generator for high energy density portable power, 26th *Army Science Conference*, December 1-4
- Ariffin, A.K., Mohamed, N.A.N., Fonna, S., 2006. Simulation of Free Piston Linear Engine Motion with Different Intake and Exhaust Port Positions. *Jurnal Kejuruteraan* 18, UKM, Malaysia pp 97-106
- Arshad, W.M., Backstrom, T., Thelin, P., Sadarangani, C., 2002, Integrated free-Piston generators: An Overview, Proceeding of the Nordic Workshop on Power and Industrial Electronics, http://www.ee.kth.se/php/modules/publication/2002/IR-EE-EME_2002_0021
- Arshad, W.M., Thelin, P., Bäckström, T., and Sadarangani, C. 2003, "Alternative electrical machine solutions for a free piston generator", *The Sixth International Power Engineering Conference (IPEC2003)*, Singapore, 27 - 29 November,
- Arshad, W.M., 2003, *A low-leakage linear transverse-flux machine for a free-piston generator*, Ph.D. thesis, ISBN 91-7283-535-4, TRITA-ETS-2003-08, ISSN 1659-674x, ISRN KTH/EME/ R 0304-SE.
- Arsie, I., Pianese, C., Rizzo, G., Flora, R., Serra, G., 1998, Development and validation of a model for mechanical efficiency in a spark ignition engine, *Society of Automotive Engineer* 99P-284
- Atkinson, C., Petreanu, S., Clark, N., Atkinson, R., McDaniel, T., Nandkumar, S., Famouri, P., "Numerical Simulation of a Two-Stroke Linear Engine-Alternator Combination," *SAE Technical Paper* 1999-01-0921, 1999.
- Atkinson, R.J., Nandkumar, S., Atkinson, C.M., and Petreanu, S., 1999, Development of linear alternator-engine for hybrid electric vehicle applications, *IEEE transactions on vehicular technology*, Vol. 48. No. 6, pp.1797- 1802

- Balling, R.J., Safieszcznski-Sobieski, J. 1994. An Algortm for solving the system-level problem in multilevel optimization, *NASA Contractor report* 195015, ICASE Report No. 94-96, pp:1-23
- Baumuller, A., and E. Schmieder, E., 2001. Field-test and market introduction of a 10 kW stirling engine as CHP-and Solar-Module, 10th *International Stirlig engine conference* 2001 (10th ISEC), 24-26 September 2001, Osnabruck, Germany, pp 106-113
- Bos, M. 2007. *Validation Gt-Power Model Cyclops Heavy Duty Diesel Engine*, MSc. Thesis Reportnumber WVT 2007, The Technical University of Eindhoven
- Brandhorst, H.W., 2007. Development of a 5 kW Free-Piston Stirling Space Convertor, *AIAA Technical Conference*.
- Braun, A. T. and Schweitzer, P. H., 1973. The Braun Linear Engine. *SAE Technical Paper* 730185.
- Bruening, D., Garnet, T., Amarashinghe, S., 2003, An infrastructure for adaptive optimization, *International Symposium on Code Generation and Optimization*, pp:265-275
- Buck, E.S., 1991. Two plus two stroke opposed piston heat engine, U.S. Patent Application No. 4,996, 953, Application filed, March 5, 1991
- Cawthorne W.R., Famouri, P., Chen, J., Clark, N.N., McDaniel, T.I., Atkinson, R.J., Nandkumar, S., Atkinson, C.M.,and Petreanu, S., 1999. Development of a Linear Alternator–Engine for Hybrid Electric Vehicle Applications, *IEEE Transaction on Vehicular technology*, Vol 48, No. 6, pp. 1797-1802
- Cawthorne, W.R., Famouri, P., Clark, N., 2001. Integrated design of linear alternator/engine system for HEV auxiliary power unit, *IEEE*, 0-7803-709, pp. 267-274
- Cawthorne, W.R. Parviz Famouri, P. Chen, J. Clark, N.N. McDaniel, T.I. Atkinson, R.J. Nandkumar, S. Atkinson, C.M. and Petreanu, S. 1999. Development of a Linear Alternator–Engine for Hybrid Electric Vehicle Applications, *IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY*, VOL. 48, NO. 6, pp. 1797-1802

- Chen, A., Arshad, W.M., Thelin, P., Zheng, P., 2004, Analysis and Optimization of a Longitudinal Flux Linear Generator for Hybrid Electric Vehicle Applications, *IEEE VTS Vehicle Power and Propulsion Symposium*, VPP 04, France October
- Clark, N., Nandkumar, S., Atkinson, C., Atkinson, R., McDaniel T., and Petreanu, S., 1998. Modeling and development of a linear engine, *ASME Spring Conference, Internal Combustion Engine Division* **30** (2), pp. 49–57.
- Clark, N., Nandkumar, S., Famouri, P. 1999. Fundamental Analysis of a Linear Two-Cylinder Internal Combustion Engine. *SAE Technical Paper* 982692.
- Clark, N., McDaniel, T., Atkinson, R., Nandkumar, S., Atkinson, C., Petreanu, S., Tennant C., Famouri, P., Modeling and Development of a Linear Engine,” ICE-Vol. 30-2 *Proceeding of the Spring Technical Conference of the ASME Internal Combustion Engine Division*, Book No. G1074B, 1998.
- Clark, N., Nandkumar, S., Atkinson, C., Atkinson, R., McDaniel, T., Petreanu, S., Famouri, P., “Operation of a Small Bore Two-Stroke Linear Engine,” *ASME* 98- ICE-120, 1998.
- Christopher M.A., Petreanu, S., Clark, N.N., Atkinson, R.J., McDaniel, T.I., Nankumar, S., and Famouri, P. 1999. Numerical Simulation of a Two-Stroke Linear Engine_Alternator Combination, *SAE Technical Paper Series*, 1999-01-0921
- Dechaumphai, P., Lim, W. 1996. Finite Element Thermal-Structural Analysis of Heated Products, *Thamasai International Journal of Science and Technology*, Vol. 1, Issue 01.
- Del Llano-Viscaya, L., Rubio-Gonzalez, C., Mesmacque, G., Cervantes-Hernandez, T., 2006, Multiaxial fatigue and failure analysis of helical compression springs, *Elsevier, Engineering Failure Analysis* 13, pp: 1303-1313
- Derek B., Garnet, T. And Amarasinghe, S. 2003. An Infrastructure for Adaptive Dynamic Optimization, *IEEE International Symposium on Code Generation and Optimization*, 265-275
- Deutsch, P., Vysoky, O., 2006. In-cycle thermodynamic model of linear combustion engine, *Proceedings of the 2006 IEEE International Conference on Control Applications* Munich, Germany, October 4-6,

- Esfahanian, V., Javaheri, A., Ghaffapour, M. 2006. Thermal Analysis of an SI Engine Piston Using Different Combustion Boundary Condition Treatments, *Science Direct, Applied Thermal Engineering* 26, pp: 277-287
- Fahs, B., Bose, S., Crum, M., Slechta, B., Spadini, F., Tung, T., Patel, S.J., Lumetta, S.S. 2001. Performance characteristic of a hardware mechanism for dynamic optimization, *Proceeding of the 34th ACM/IEEE International Symposium on Microarchitecture*, 2001, pp:16-27
- Farmer, H. O., 1947. Free-Piston Compressor-Engines." *Proceedings of the Institution of Mechanical Engineers*, vol. 156, pp. 253-271
- Fathallah, A.Z.M., Bakar, R.A., 2009, Prediction Studies for the Performance of a Single Cylinder High Speed Spark Ignition Linier Engine with Spring Mechanism as Return Cycle, *American J. of Engineering and Applied Science*, 2 (4) pp720-727
- Ferguson, C.R. 1986. *Internal combustion engine applied thermosciences*. New York. Jon Wiley & Sons
- Ferguson, C.R., Kirkpatrick, A.T., 2001, *Internal combustion engine applied thermosciences*, 2nd Ed, Jon Wiley & Sons.
- Flynn, G. Jr., 1957, "Observations on 25,000 Hours of Free-Piston-Engine Operation", *SAE Transactions*, Volume 65, pp 508-515.
- Fonna,S., Mohammed, N.A.N. Arifin., A.K., 2005. Cycle effect inversigation of free piston linear engine, *National Seminar on Computational & experimental Mechanic (CEM)*, bangi, Malaysia may 17-18, pp:249-257
- Fredriksson J., and Denbratt I., 2004, Simulation of two-stroke free piston engine, *SAE series publication* 2004-01-1871
- Frey, D. N., Klotsch, P., Egli, A., 1957. "The Automotive Free-Piston-Turbine Engine", *SAE Transactions*, Volume 65, pp 628-634.
- Galitello K.A., 1989. Two stroke cycle engine, U.S. Patent Application No. 4,876, 991, Application filed, October 31, 1989
- Gamma., T., 2004, GT-Power manual, Version 6.1, *Gamma Technologies*

- Goldsborough S.S., Van Blarigan, P., 2003, Optimizing the Scavenging System for a Two-Stroke Cycle, Free Piston Engine for High Efficiency and Low Emissions: A Computational Approach, *SAE Technical paper* 2003-01-0001
- Gotoh, T. Imaizumi, T. 2000. Optimization of force action line with new spring design on the macpension for riding comfort, *SAE Technical Paper Series*, 2000-01-0101
- Hansson J., Leksel M., Carlsson F., 2005, Minimization power pulsation in a free piston energy converter, *proceedings of the 11th European Conference on power electronics and Applications (EPE05)*, Dresden, Germany.
- Hansson J., Leksel M., Carlsson F., Sadarangani C., 2005, Operation Strategies for a free piston energy Converter, *proceeding of the fifth International Symposium on Linear Drivers for Industry Applications (LDIA05)*, Kobe-Awaji, Japan
- Hansson J., Leksel M., 2006, Performance of a Series Hybrid electric vehicle with a free-piston energy converter, *Proceedings of the 2006 IEEE Conference on Vehicle Power and Propulsion (VPPC2006)* Windsor, UK.
- Hansson, J., Leksel, M., Carlsson, F., 2005, Minimizing Power Pulsations in a Free Piston Energy Converter, *Proceedings of the 11th Europea Confrence Power Electronic and Applications* (EPE05 September 2005
- Heintz, R. P., 1989 “Free-Piston Engine Pump”, U.S. Patent Application No. 150,390, Application filed May 16, 1980; U.S. Patent No. 4,369,021, Patent Issued January 18, 1983.
- Henry W. Brandhorst, H.W. and Chapman, P.A. 2008. New 5k W free-piston Stirling space convertor developments, *Science direct, Acta Astronautica* 63 (2008) 342 – 347
- Heywood, J.B. 1988. *Internal combustion engine fundamentals*. USA: McGraw-Hill.
- Hibi, A., Ito, T., 2004. Fundamental test results of a hydraulic free piston internal combustion engine, *Proc. Instn Mech. Engrs* Vol. 218 Part D: J. Automobile Engineering
- Hoag, K.L. 2006. *Vehicular Engine Design Powertrain*. New York. Springer Wien.
- Hoshino, T., 2003. Preliminary test results on 200 We free-piston stirling engine converter, *AIAA 2003-6094, 1st International Energy Conversion Engineering Conference* 17-21 August, Portsmouth, Virginia.

- Houdyschell, D., 2000, *A Diesel Two-Stroke Linear Engine*, Master thesis in Mechanical Engineering, Department of Mechanical and Aerospace Engineering, West Virginia University
- Hu, Y., Hibi, A., 1990. Hydraulic free piston Internal combustion Engine (Outline of the Fundamental test apparatus with Oppose Pistons), *JSME* 56, 89-1131 B Series pp 343-346
- Hu, Y., Hibi, A. 1990. Hydraulic free piston Internal combustion Engine (Experiment Investigation on the Fundamental test apparatus with Opposed piston), *JSME* 56, 89-1372 B Series pp 339-344
- Iliev, M. D., Kervanbashiev, S. S., Karamanski, S. D., Makedonski, F. M., “Method And Apparatus For Producing Electrical Energy From A Cyclic Combustion Process Utilizing Coupled Pistons Which Reciprocate In Unison”, U.S. Patent Application No. 431,119 (CUV “Progress”), Application filed September 30, 1982; U.S. Patent No. 4,532,431 (CUV “Progress”), Patent Issued July 30, 1985.
- Innas, 2010, Two cars: same weight, same size, same engine, same traction, same performance, was download in May 6, 2010, available at: <http://www.innas.com/Assets/files/Hydriddbrochure.pdf> (10 January 2010)
- Issakson S, 2002. Simulation of a Two-Stroke Compression Ignition Hydraulic Free Piston Engine, *GT-Suite user conference, October 30*
- Jakob F and I. Denbratt, 2004. Simulation of two-stroke free piston engine, *SAE Technical paper series*, 2004-01-1871
- Juvinall, R.C. and Marshek, K.M. 2006, *Fundamental of Machine Component Design*, John Wiley & Sons Asia, 4th Ed, ISBN: 13978-0-471-74285-2, pp: 290-339 and 469-492
- Klemann, A.P., Dabadie, J.C., Henriot, S., 2004. Computational Design Studies for a High Efficiency and Low-Emissions Free Piston Engine Prototype, *SAE Technical paper series*, 2004-01-2928
- Kos, F. J., 1991. “Computer Optimized Hybrid Engine”, U.S. Patent Application No. 556,872, Application filed July 20, 1990; U.S. Patent No. 5,002,020, Patent Issued March 1991.

- Kowalewicz, A., 1984, *Combustion systems of high-speed piston I.C. engine*, Elsevier Science Publishers, Amsterdam, the Netherlands
- Kwankaomeng, S. 2008. *Design of a free-piston stirling engine-pump*, PhD Thesis, University of Wisconsin-Madison
- Lane, N.W., Beale, W.T., 1997, Free-piston Stirling design features, *8th International Stirling Engine Conference*, May 27-30, University of Ancona, Italy
- Larrowe, V.L. and M.M. Spancer, 1958. *Analog computer simulation of a free-piston engine*, The University of Michigan, Industry program of the college of engineering, IP-239
- London, A. L. and Oppenheim, A. K., 1952. The Free-Piston Engine Development-Present Status and Design Aspects. *Transactions of the ASME*, vol. 74, no. 2, pp. 1349-1361. *Based upon ASME Technical Paper 52-S-17.*
- Martin Goertz, M., Peng, L., 2000. Free Piston Engine Its Application and Optimization, *SAE Technical Paper Series*, 2000-01-0996
- Mikalsen, R., and Roskilly, A.P., 2008. The design and simulation of a two-stroke free-piston compression ignition engine for electrical power generation, *Science Direct, Applied Thermal Engineering* 28, pp. 589-600
- Mikalsen, R., and Roskilly, A.P., A review of free-piston engine history and applications, Science Direct, *Applied Thermal Engineering* 27 (14–15) (2007), pp. 2339–2352
- Mikalsen, R., Roskilly, A.P., 2008, Coupled Dynamic-multidimensional modeling of free-piston engine combustion, *Applied Thermal Engineering* 85, Science Direct, 89-95
- Nankumar S., 1998, *Two stroke Linear Engine*, MSME Thesis, The College of Engineering and Mineral Resources, West Virginia University.
- Nandkumar, S., 1998, *Two-Stroke Linear Engine*, Master thesis in Mechanical Engineering, Department of Mechanical and Aerospace Engineering, West Virginia University
- Němeček, P., Vysoký, O., 2007, Control of two-stroke free-piston generator, was down loaded in April, 12, 2010, available at:
http://www3.fs.cvut.cz/web/fileadmin/documents/12241-BOZEK/publikace/2007/2007_076_01.pdf

- Nerstrom, J. S., "Two-Cycle Internal Combustion Engine Including Means For Varying Cylinder Port Timing", U.S. Patent Application No. 376,705 (Outboard Marine Corporation), Application filed May 10, 1982; U.S. Patent No. 4,516,540 (Outboard Marine Corporation), Patent Issued May 14, 1985.
- Nik A.M.N., A.K. Ariffin, S. Fonna, 2006, Simulation of a Two-Stroke Spark Ignition Free Piston Linear Motion, *Jurnal Teknologi*, 44 (Jun) 2006, Universiti Teknologi Malaysia, 27-40
- Noda, N., Hetnarski, R.B., and Tanigawa, Y.2003. *Thermal Stress*. New York: Taylor and Francis, 2nd Ed.
- Noren, O.B. and R.L. Erwin, 1958. The future of the free-piston engine in commercial vehicles, *SAE Transactions* **66**, pp. 305–314.
- Parades, M., Sarfor, M., Masclet, C., 2001, An optimization process for extension spring design, *ELSEVIER, Comput. Methods Appl. Engrg.* 191, pp:783-797
- Pascara, R.P. 1928. Motor compressor apparatus. US Patent 1,657,641
- Pascara, R. P., 1941. Motor Compressor of the Free Piston Type." U. S. Patent 2,241,957.
- Petele, M. 2009. Spring Calculation,
<http://www.mitcalc.com/doc/springs/help/en/springs.htm> , Copyright 2003-2009, all rights reserved.
- Petreanu, S., 2001, *Conceptual analysis of a four-stroke linear engine*, Doctor of Philosophy thesis in Mechanical engineering, Department of Mechanical and Aerospace Engineering, West Virginia University
- Pohl S.K., Markus Graf, M., 2005. Dynamic Simulation of a Free-Piston Linear Alternator in Modelica, *Proceedings of the 4th International Modelica Conference*, Hamburg, March 7-8,
- Porterio. J.L. 2010. Spring design optimization with fatigue, Master Science Thesis, Mechanical Engineering, University of South Florida.
- Qingfeng L, J. Xiao, Z. Huang, 2008. Simulation of a Two-Stroke Free-Piston Engine for Electrical Power Generation, *Energy & Fuels* 22, pp: 3443–3449
- Rao, S.S., 1996, *Engineering optimization theory and practice*, 3rd Ed, John Wiley and Sons.

- Reddy, J.N. 2006. *An Introduction to the Finite Element Method*, McGraw Hill, 3rd Ed, International Edition, Singapore.
- Rittmaster, P. A., Booth J. L. 1980. Hydraulic Engine”, U.S. Patent Application No. 110,771, Application filed January 9, 1980; U.S. Patent No. 4,326,380, Patent Issued April 27, 1982.
- Ruzicka, M., Doubrava, K., 2005, Loading regimes and designing helical coiled springs for safe fatigue life, *RES. AGR.ENG*, 51,(2) pp:50-55
- Saiful A.Z., M.N. Karsiti., B.S. Iskandar., A.R.A. Aziz, 2008, Starting of Free-Piston Linear Engine-Generator by Mechanical Resonance and Rectangular Current Communication, *IEEE Vehicle and Propulsion Conference (VPPC)*, September 3-5, Harbin, China,
- San, M.N. 2008. Design and Kinematics Analysis of Piston. *GMSARN International Conference on Sustainable Development: Issues and Project for the GMS*
- Slaby, J.G., 1984., Overview of NASA Lewis Research Center Free-Piston Stirling Engine Activities, *Nineteenth Intersociety Energy Conversion Engineering Conference cosponsored by the ANS, ASME, SAE, IEEE, AIAA, ACS, and AIChE* San Francisco, California, August 19-24
- Stone, R. 1997. *Introduction to internal combustion engines*. USA: Society of Automotive Engineers, Inc.
- Underwood, A.F, 1957. The GMR 4-4 “HYPREX” engine – A concept of the free-piston engine for automotive use, *SAE Transactions* **65**, pp. 377–391.
- Van Blarigan, P., Paradiso, N., and Goldsborough, S. S., 1998. Homogeneous Charge Compression Ignition with a Free Piston: A New Approach to Ideal Otto Cycle Performance, *SAE Technical Paper* 982484.
- Van Blarigan, P., 2001. Free-Piston Engine. U. S. Patent 6,199,519.
- Van Blarigan, P., 1999. Homogeneous charge compression ignition with a free piston: a new approach to ideal Otto cycle performance, *Proceedings of the 1999 U.S DOE Hydrogen Program Review* NREL/CP-570-26938

- Van Blarigan, P., Paradiso, N., and Goldsborough, S.S., 1998, Homogeneous Charge Compression Ignition with a Free Piston: A New Approach to Ideal Otto Cycle Performance, SAE Technical Paper 982484
- Van Blarigan, P., 1999, Homogeneous Charge Compression Ignition with a Free Piston: A New Approach to Ideal Otto Cycle Performance, *Proceedings of the 1999 U.S DOE Hydrogen Program Review* NREL/CP-570-26938
- Van Blarigan, P., 2002, Advanced Internal Combustion Electric generator, Proceedings of the 2002 U.S. DOE Hydrogen Program Review NREL/CP-610-32405
- Wood, J.G., Lane N.W., and Beale, W.T., 2001, Preliminary Design of a 7 kWe Free-Piston Stirling Engine with Rotary Generator Output, *the proceedings of the 10th International Stirling Engine Conference (10th ISEC)*, 24 - 27 Sept. 2001, Osnabrück/ Germany
- Wood, J.G., and Lane, N., 2004, Advanced Small Free-Piston Stirling Convertors for Space Power Applications, *American Institute of Physics*, <http://proceedings.aip.org/proceedings/confproceed/699.jsp>
- Yamada, Y., Saitoh, T., Ishida, M. Uzumachi, K., Suzuki, H., Teratoko, K., 2000, Improve fatigue strength of valve springs and sheet springs by application of a new fine shot peening technology, *SAE Technical Paper series*, 2000-01-0791,